From the ASTRONOMICAL JOURNAL
69, No. 2, 1964, March—No. 1317
Printed in U. S. A.

4P

NsG-142-61

A Photographic Optical Semidiameter of Venus

BRADFORD A. SMITH
Research Center, New Mexico State University, University Park, New Mexico

N64-28975

(Received 5 November 1963)

ABST

28975

Measurements of the optical diameter of Venus are generally free from the usual systematic errors when such measurements are made of the illuminated cresent at phase angles approaching 180°. Fifty-four photographic images obtained within a few days of inferior conjunction in November 1962 have been measured across the diameter connecting the geometric cusps. An optical semidiameter of 8.″486±0.″004 (p.e.) at unit distance is found, and is in some disagreement with visual observations. A radius of 6050 km for the solid globe of Venus and a resulting mean density of 5.25 g/cm³ is inferred.

CODE NONE Cat. 05

Author

1. INTRODUCTION

DETERMINATIONS of the optical semidiameter of Venus may conveniently be classified according to three basic types of measurements: (1) the diameter of the opaque disk when Venus is seen in transit against the sun, (2) the diameter of the illuminated disk at relatively small phase angles, and (3) measurements across the cusps when the phase angle approaches 180°. As an example, the ephemeris semidiameter of 8.″41 at unit distance was adopted from the corrected heliometer measurements made by Auwers (1894) during the transits of 1874 and 1882. One might also wish to include transit contact measurements, and the occultation of α Leonis by Venus, as reported by Martynov (1960, 1962) and de Vaucouleurs (1961). However, the "black-drop" effect seriously impairs the accuracy of the contact method, and de Vaucouleurs (1963) has stated that the accurately determined occultation semidiameter is difficult to relate to the optical semidiameter.

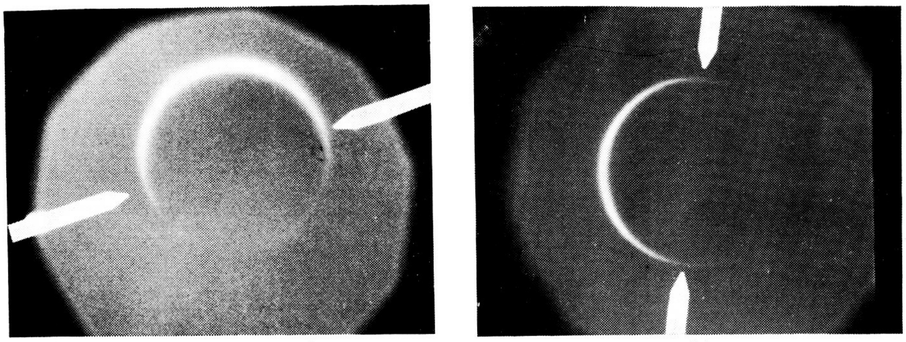
Considering now the three basic types of measurements, it will be noted that seeing and irradiation will tend to diminish the observed diameter of the disk in transit, and expand the observed diameter of the illuminated disk. Additionally, limb brightening in the violet and limb darkening in the red will have their obvious effects on measurements of the illuminated disk. It is difficult to allow for these systematic errors, which occur in both visual and photographic observations. Measurements across the thin crescent, when the true geometric cusps can be observed or photographed, however, are remarkably insensitive either to seeing, irradiation (and its photographic analogue, turbidity), or limb effects. During favorable inferior conjunctions, the cusps extend well beyond their geometric positions, rapidly closing to form a complete ring as Venus approaches a distance of four degrees from the sun. This phenomenon, a twilight effect in the scattering region above the opaque cloud surface on Venus, readily permits photography of the geometric cusps, which would otherwise be too weak to be recorded. Since the problem is now reduced to that of measuring the separation between two bright lines, themselves unresolved, the systematic errors caused by irradiation and limb effects will vanish and the effects of seeing will be greatly diminished.

2. OBSERVATIONS, MEASUREMENT, AND REDUCTION

Throughout a month, centered on the favorable inferior conjunction of 12 November 1962, over 6000 images of Venus were taken at the New Mexico State University for the purpose of studying this scattering layer above the opaque cloud cover. Of special interest among these plates, taken at the 20-m Cassegrainian focus of the University's 12-in. Fecker reflector (f6.7 primary focus), were those obtained within a few days of the actual conjunction. The use of special shielding equipment permitted the full aperture to be used with Venus as close as four degrees from the sun. To the best of the writer's knowledge, Venus had not previously been photographed this close with an aperture as large as 12 in.

During this optimum interval pronounced extensions of the cusps were recorded, thereby permitting these images to be used for diameter measurements. A total of 54 of the better images in green and red light were selected from plates taken on five of the days when Venus was within seven degrees of the sun. These images were measured with a model 422-D Mann comparator (digitized through a Telecomputing model 15-A head) across a diameter connecting the instaneous positions of the geometric cusps (see Fig. 1). Since the true angular width of the illuminated arc in the vicinity of the cusps lies well below the resolution limit of the photographic instrument, it was only necessary for the comparator operator to bisect the recorded width of the arc at each cusp. Actually, five individual readings were taken and averaged for each cusp. The linear separations between the cusps were then corrected for differential refraction at the appropriate position angle, and multiplied by the true distance from the earth to Venus, thereby reducing each measured diameter to an equivalent diameter at unit distance. Although of marginal significance, a reduction from topocentric to geocentric origins was included. The average of the reduced diameter measurements was 1.6553 mm±0.0007 (p.e.), while the mean probable error of measurement was 0.0011 mm, or only 0.0003

RC#4



(a) (b)

FIG. 1. (a) Venus 4.0 deg from the sun at 1933 UT on 12 November 1962. The complete atmospheric ring can be seen. (b) Venus 6.9 deg from the sun at 1537 UT on 16 November 1962. Both photographs were taken in red light using a IV-E plate and an OG-2 filter. The arrows indicate the positions of the geometric cusps. North is at the top.

mm when reduced to unit distance. Thus it will be noted that the dispersion in the measured diameters was not primarily a result of uncertainties in measurement, but rather a dispersion in the true diameters of the images, most probably caused by differential excursion of the image in the focal plane. A summary of the plates containing the measured images is given in Table I. With each plate in Table I is given the approximate time that the plate was taken, the Eastman plate–Schott filter combination, the effective wavelength of sensitivity, the number of images measured, and the average diameter reduced to unit distance. Each plate contains 30 images and required an average interval of 18 min to complete.

Although the average diameter given by the green images is slightly smaller than that given by the red, there is agreement within the probable errors, thereby suggesting that the medium which makes the geometric cusps visible is essentially scattering independently of wavelength at the observable heights. From this it may be inferred that the mean size of the scattering particles is large when compared with the wavelength of visible light. When the images were grouped by date it was found that the day to day diameter variations slightly exceeded the probable errors of the daily groups. Although this offers a suggestion that the height of the top of the cloud layer may vary with time, it should be noted that the numbers of images in the daily groups

TABLE I. Summary of measured Venus plates.

Plate No.	Time (UT)	Plate–filter	$\lambda_{eff}(\mu)$	No. of images	Average diameter $\Delta=1$
F2491	11 Nov., 16.8 h.	IV-E/OG-2	0.630	3	1.6543 mm
F2501	12 Nov., 15.9 h.	IV-E/OG-3	0.635	3	1.6569
F2502	12 Nov., 16.3 h.	III-F/RG-2	0.665	3	1.6520
F2505	12 Nov., 17.6 h.	I-N/RG-5	0.750	1	1.6608
F2509	12 Nov., 19.6 h.	IV-E/OG-2	0.630	6	1.6542
F2510	12 Nov., 20.0 h.	IV-G/OG-4	0.545	3	1.6568
F2519	13 Nov., 17.4 h.	III-F/RG-2	0.665	3	1.6517
F2520	13 Nov., 17.8 h.	IV-E/OG-2	0.630	5	1.6522
F2521	13 Nov., 18.1 h.	IV-G/OG-4	0.545	3	1.6502
F2525	14 Nov., 17.4 h.	IV-E/OG-2	0.630	6	1.6590
F2527	14 Nov., 18.2 h.	III-F/RG-2	0.665	5	1.6620
F2528	14 Nov., 18.6 h.	IV-G/OG-4	0.545	4	1.6539
F2530	14 Nov., 19.6 h.	IV-E/OG-2	0.630	6	1.6553
F2536	16 Nov., 15.7 h.	IV-E/OG-2	0.630	3	1.6566

are somewhat too small for acceptable statistical significance.

In order to make full use of the small probable error in the diameter of the Venus images, it was necessary to redetermine the plate scale of the Cassegrainian instrument to a higher degree of accuracy than had previously been achieved. An analysis of the variables contributing to a temperature coefficient for the plate scale showed that the coefficient was sufficiently small as to have a negligible effect over the range in temperature encountered during the Venus photography.

The equivalent focal length of a Cassegrainian system may be given by

$$F'=\frac{FD}{d}+\frac{F^2}{d}-F,$$

where F is the focal length of the primary mirror, D is the distance between the primary mirror and the secondary focal plane, and d is the intercept distance from the primary focal plane to the secondary mirror. By taking partial derivatives and assuming that both optical components are at thermal equilibrium, the fractional change in the equivalent focal length is given by

$$\frac{\Delta F'}{F'}=\left[\alpha_g+\left(\frac{A-1}{A^2}\right)\frac{D}{d}(\alpha_m-\alpha_g)\right]\Delta t,$$

where α_g is the temperature coefficient of Pyrex, α_m is the temperature coefficient of the structural material separating the primary mirror and the plate holder, A is the amplification, and Δt is the change in temperature. Noting that $F-d$ is the separation L between the primary and secondary mirrors and that $(L+D)/d$ is the amplification A, the temperature coefficient for the plate scale of a Cassegrainian system is

$$\alpha_g+\left(\frac{A-1}{A}\right)\frac{D}{L+D}(\alpha_m-\alpha_g).$$

It is assumed here that the focus is constantly maintained at the secondary plane, thereby removing the necessity of accounting for tube expansion and contrac-

tion. The temperature coefficient for the Fecker telescope is given by the above as $6.3\times10^{-6}\,°C^{-1}$.

As part of the standard photographic procedure, the Fecker telescope is continuously refocused by translation of the secondary mirror along the optical axis, thereby correcting for the changing length of the telescope tube. Nevertheless, the computed coefficient assumes equilibrium conditions, a situation not always realized. As a precautionary measure, therefore, the calibration plates were taken over the same temperature range as occurred when the Venus plates were taken. (The air temperature in the immediate vicinity of the telescope had been recorded continuously throughout the photographic program.)

Ten pairs of stars in $+15°$ to $+20°$ zone of the Yale Catalogue were selected for the initial calibration. The pairs, chosen for similar magnitudes and spectral class as well as small probable errors in proper mention, were individually photographed 10 to 20 times, then measured on the Mann comparator and corrected for differential refraction. The probable errors in the average separation of each pair were of the same order as those found in the Venus measurements. The angular extent, however, being roughly 300″ or five times greater than the observed diameter of Venus, established a plate scale with a fractional probable error several times smaller than that obtained in the measurement of the Venus images.

When the plate scale was applied to the Venus measurements, it was found that the semidiameter at unit distance was considerably larger than the $8\overset{''}{.}43 \pm 0\overset{''}{.}02$ (p.e.) found by de Vaucouleurs (1963) from a study of all available data. It was therefore decided to repeat the calibration of the plate scale using stars in the Pleiades Cluster. Nine pairs of stars were selected, with the positions being taken from the Yale Catalogue and the AGK2. The proper motions used were those given by Hertzsprung (1947). The selection and photographic procedure was identical to that used in the first calibration series. As was mentioned earlier, the calibration plates of both series were taken over the same range of temperature that was encountered throughout the Venus photography. The temperature coefficient, incidentally, was found to be indetectable, confirming the predictions established by the computations.

The second calibration series fully confirmed the original, and the plate scale can be given as $10\overset{''}{.}253/\text{mm}\pm0\overset{''}{.}001/\text{mm}$ (p.e.). The semidiameter of Venus at unit distance was thus found to be $8\overset{''}{.}486\pm0\overset{''}{.}004$ (p.e.).

A normalized distribution of the semidiameters obtained from the 54 measured images is given by the heavy line in Fig. 2. The lighter line shows a Gaussian distribution having the same standard deviation σ as was found for the measured images. It will be noted that the measured distribution gives a reasonably good fit to the Gaussian curve and that no skewness is evident. The probable error of the average semidiameter, and the average of the probable errors of the cusp measurements by the comparator operator are indicated. For comparison the semidiameters given by Auwers (ephemeris value) and de Vaucouleurs (1963) are included.

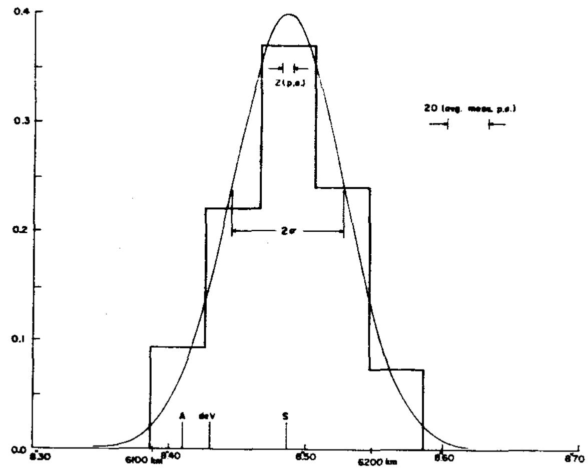


FIG. 2. The normalized distribution of the semidiameters of the 54 measured images (heavy line) is compared with a Gaussian distribution (light line) having the same standard deviation σ. The probable error of the semidiameter and the average probable error of measurement are indicated. Also included are the semidiameters of Auwers and de Vaucouleurs.

3. DISCUSSION

When expressed in linear units, the radius given by de Vaucouleurs (1963) is 6114 ± 14 km. The radius of Venus from the observations reported here is 6155 ±3 km or approximately 40 km greater. Yet, it would seem unlikely that a discrepancy of this magnitude could reflect a true variation in the height of the top of the cloud layer. Indeed, inquiry into the cause of the discrepancy brings up the question as to precisely what is being measured. Through studies of cusp prolongations near inferior conjunction, it has been possible to obtain a crude picture of the optically thin scattering region which lies above the opaque cloud cover on Venus. Visual studies by Russell (1899) indicate a relatively bright haze layer extending upward to a height of approximately 1 km above the opaque surface. Photographic observations by Edson (1959) have shown the existence of a weaker layer which extends slightly more than 10 km above the opaque surface, and more recently Smith and Bains (1963) have encountered the probable existence of very weak scattering at heights as great as 30 km. In general, heights greater than 10 km are observed only when Venus is greater than 10° from the sun where the terrestrial sky background is less severe. As defined by studies of cusp prolongations, the opaque surface is the limiting level through which sunlight can pass, scatter in the overlying optically thin haze, and still be visible against the observer's bright terrestrial sky.

tion. The temperature coefficient for the Fecker telescope is given by the above as $6.3\times10^{-6}{}^{\circ}C^{-1}$.

As part of the standard photographic procedure, the Fecker telescope is continuously refocused by translation of the secondary mirror along the optical axis, thereby correcting for the changing length of the telescope tube. Nevertheless, the computed coefficient assumes equilibrium conditions, a situation not always realized. As a precautionary measure, therefore, the calibration plates were taken over the same temperature range as occurred when the Venus plates were taken. (The air temperature in the immediate vicinity of the telescope had been recorded continuously throughout the photographic program.)

Ten pairs of stars in $+15°$ to $+20°$ zone of the Yale Catalogue were selected for the initial calibration. The pairs, chosen for similar magnitudes and spectral class as well as small probable errors in proper mention, were individually photographed 10 to 20 times, then measured on the Mann comparator and corrected for differential refraction. The probable errors in the average separation of each pair were of the same order as those found in the Venus measurements. The angular extent, however, being roughly 300″ or five times greater than the observed diameter of Venus, established a plate scale with a fractional probable error several times smaller than that obtained in the measurement of the Venus images.

When the plate scale was applied to the Venus measurements, it was found that the semidiameter at unit distance was considerably larger than the 8″.43 ±0″.02 (p.e.) found by de Vaucouleurs (1963) from a study of all available data. It was therefore decided to repeat the calibration of the plate scale using stars in the Pleiades Cluster. Nine pairs of stars were selected, with the positions being taken from the Yale Catalogue and the AGK2. The proper motions used were those given by Hertzsprung (1947). The selection and photographic procedure was identical to that used in the first calibration series. As was mentioned earlier, the calibration plates of both series were taken over the same range of temperature that was encountered throughout the Venus photography. The temperature coefficient, incidentally, was found to be indetectable, confirming the predictions established by the computations.

The second calibration series fully confirmed the original, and the plate scale can be given as 10″.253/mm±0″.001/mm (p.e.). The semidiameter of Venus at unit distance was thus found to be 8″.486±0″.004 (p.e.).

A normalized distribution of the semidiameters obtained from the 54 measured images is given by the heavy line in Fig. 2. The lighter line shows a Gaussian distribution having the same standard deviation σ as was found for the measured images. It will be noted that the measured distribution gives a reasonably good fit to the Gaussian curve and that no skewness is evident. The probable error of the average semidiameter, and the average of the probable errors of the cusp measurements by the comparator operator are indicated. For comparison the semidiameters given by Auwers (ephemeris value) and de Vaucouleurs (1963) are included.

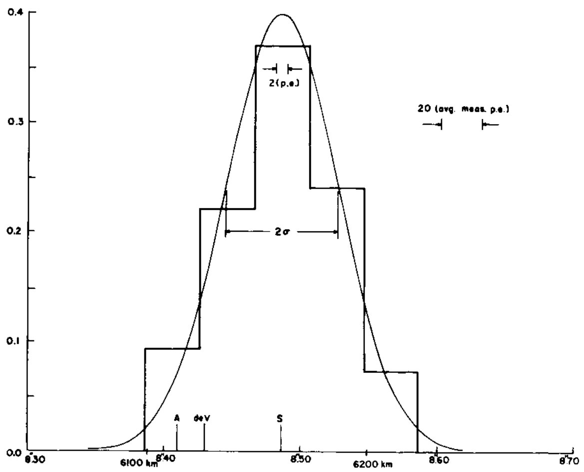


FIG. 2. The normalized distribution of the semidiameters of the 54 measured images (heavy line) is compared with a Gaussian distribution (light line) having the same standard deviation σ. The probable error of the semidiameter and the average probable error of measurement are indicated. Also included are the semidiameters of Auwers and de Vaucouleurs.

3. DISCUSSION

When expressed in linear units, the radius given by de Vaucouleurs (1963) is 6114±14 km. The radius of Venus from the observations reported here is 6155 ±3 km or approximately 40 km greater. Yet, it would seem unlikely that a discrepancy of this magnitude could reflect a true variation in the height of the top of the cloud layer. Indeed, inquiry into the cause of the discrepancy brings up the question as to precisely what is being measured. Through studies of cusp prolongations near inferior conjunction, it has been possible to obtain a crude picture of the optically thin scattering region which lies above the opaque cloud cover on Venus. Visual studies by Russell (1899) indicate a relatively bright haze layer extending upward to a height of approximately 1 km above the opaque surface. Photographic observations by Edson (1959) have shown the existence of a weaker layer which extends slightly more than 10 km above the opaque surface, and more recently Smith and Bains (1963) have encountered the probable existence of very weak scattering at heights as great as 30 km. In general, heights greater than 10 km are observed only when Venus is greater than 10° from the sun where the terrestrial sky background is less severe. As defined by studies of cusp prolongations, the opaque surface is the limiting level through which sunlight can pass, scatter in the overlying optically thin haze, and still be visible against the observer's bright terrestrial sky.

This opaque surface can be identical to the disk observed during solar transits only if the boundary between the optically thick cloud cover and the thin scattering region is well defined. If not, the diameter observed during solar transits would be expected to be less than that measured at the thin crescent phase, even after the proper allowances are made for irradiation in the case of the former. The magnitude of the systematic difference would be partially dependent upon the gradient of the extinction within the cloud layer. Such a model might explain a part of the discrepancy in the semidiameters derived from different observational techniques. Nevertheless, although some of the determinations incorporated into de Vaucouleur's (1963) value were derived from transit observations, it must also be said that some came from visual micrometer measurements across the cusps of the thin crescent, and that many of the latter also contribute to the discrepancy. Finally, the possibility that the height of the top of the opaque cloud cover may exhibit at least some variation with time cannot be excluded. Therefore, the photographic program reported here will be repeated during the even more favorable inferior conjunction in June 1964.

The highest haze levels photographed during the interval in which the 54 measured images were obtained, extended approximately 10 km above the cloud surface. Since the intensity of these scattering layers decreases with height, it is reasonable to assume that the measured semidiameter corresponds to a level roughly 5 km above the effective upper surface of the cloud cover on Venus. In reporting the results of the Mariner II project, the Staff of the Jet Propulsion Laboratory (1963) have estimated 100 km as the height of the top of the opaque cloud cover above the solid surface of Venus, and give 0.81485 ($\oplus = 1$) for the mass of the planet. From this it may be inferred that the radius of the solid globe of Venus is approximately 6050 km and that its mean density is 0.952 ($\oplus = 1$) or 5.25 g cm^{-3}.

ACKNOWLEDGMENTS

The writer's thanks are due A. S. Murrell, Chief Observer; J. D. Hartsell, and T. C. Bruce for their part in the photography of Venus, and again to J. D. Hartsell for the major part of the computational work.

The 12-in. Fecker reflector is made available to the New Mexico State University by the United States Army Research Office (Durham) under Grant No. DA-ARO(D)-31-124-G41.

The work reported here was supported entirely by the National Aeronautics and Space Administration, whose support is hereby gratefully acknowledged.

REFERENCES

Auwers, A. 1894, *Astron. Nachr.* **3214**, 359.
Edson, J. B. 1959, *Proceedings of the Lunar and Planetary Exploration Colloquium* (North American Aviation, Downey, California), Vol. 1, No. 5, p. 22.
Hertzsprung, E. 1947, "Catalogue de 3259 Étoiles dans les Pléiades," *Ann. Sterrew. Leiden* **19**, Part I.
Jet Propulsion Laboratory, Staff of. 1963, *Mariner, Mission to Venus* (McGraw-Hill Book Company, Inc., New York).
Martynov, D. Ya. 1960, *Astron. Zh.* **37**, 848.
——. 1962, *ibid.* **39**, 653.
Russell, H. N. 1899, *Astrophys. J.* **9**, 284.
Smith, B. A., and Bains, W. E. 1963 (to be published).
de Vaucouleurs, G. 1961, "Final Report on the Occultation of Regulus by Venus, July 7, 1959" (AFCRL-227) by D. H. Menzel and G. de Vaucouleurs, Harvard College Observatory, Cambridge, Massachusetts.
——. 1963 (private communication).